A Conceptual Framework for a Design Travelling Fire for Large Compartments with Fire Resistant Islands

A CONCEPTUAL FRAMEWORK FOR A DESIGN TRAVELLING FIRE FOR LARGE COMPARTMENTS WITH FIRE RESISTANT ISLANDS

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ABSTRACT

This paper presents a new conceptual framework for travelling fires in large compartments with fire resistant islands in order to ensure that the structure is able to resist more realistic fire exposures expected in such compartments, commonly found in modern office buildings. The key guiding principle in developing the proposed design fire for large compartments is to achieve a good balance between the enormous complexity and variability of such fires against the practicability and simplicity required by a structural engineer in safely characterising this load.

INTRODUCTION

Many studies of large compartments in fire carried out over the past two decades show that fires in such compartments have a great deal of non-uniformity, unlike the homogeneous compartment temperature assumption commonly made in the current fire safety engineering practice[1–3]. In general, large compartment fires burn locally and tend to move across entire floor plates over a period of time. This kind of fire scenario is beginning to be idealized as “travelling fires”. Travelling fires in real life have been observed in several structural failures especially from 2000: the World Trade Center Towers[4] in New York City in 2001, the Windsor Tower[5] in Madrid in 2005, and the Faculty of TU Delft Architecture building[6] in Netherlands in 2008. Looking closely at an example of an open modern building, i.e. the Informatics Forum opened at the University of Edinburgh in 2009, a statistical survey indicated that traditional fire safety design methods were applicable to only 8% of the total volume of the building[7]. This naturally implies the urgency of greater research effort on developing the so-called travelling fire methodology.

In 2013 a series of experiments labelled as ‘Real Fires for Safety Design of Tall Buildings’[8] were conducted at the Building Research Establishment (BRE) in UK, for obtaining a better understanding how a fire progresses in a large compartment and affects the temperature distribution spatially and temporally. In 2015, another experiment called the Tisova Fire Test[9] was conducted in the Czech Republic inside a 4-storey concrete frame building, in order to test the travelling fire methodology put forward by Stern-Gottfried & Rein[10]. Two main theoretical representations of travelling fire models can be found in literature, hereinafter referred to as: Clifton’s model[11]; and Rein’s model[10]. Clifton developed a fire model which divides the whole large compartment into several design areas, which are then subjected to parametric fires individually and sequentially. In Rein’s model, Alpert’s correlation is adopted to calculate far field smoke temperature, and a uniform temperature ($800℃ - 1200℃$) is assumed for the near field.

However, both models necessarily neglect some aspects of the fire dynamics. For instance the *accumulation* of a hot smoke layer is ignored in both models. In Clifton’s model, all elements in one ‘firecell’ (one design area) share the same fire exposure history. In Rein’s model the uniform $800℃ - 1200℃$ assumption is very generic. Furthermore, due to computational complexity for fully coupled analysis, neither of the travelling fire models have thus far been coupled to global structural response, although both travelling fire models have been developed for application to structural design.

This paper introduces a new travelling fire model implemented in a generalised structural fire framework. A new kind of travelling fire is proposed, based on a mobilised version of Hasemi's localized fire model[12], combined with a simple smoke layer calculation for the areas of the compartment away from the fire. This combined fire model enables the analysis to capture both spatial and temporal changes of the thermal field which is then automatically coupled to a thermomechanical analysis using the software framework OpenSees. The heat fluxes received by each structural member in a large compartment using this approach should provide greater fidelity with realistic conditions yet in a computationally tractable form.

NEW TRAVELLING FIRE MODEL

The proposed design fire is idealized as a localized fire plume with characteristics that include: a predetermined plume propagation trajectory along which it travels; variable fuel load distribution along the trajectory; and consideration of smoke accumulation under the ceiling.

It is proposed here to combine Hasemi's model for determining the temperature evolution in structural members close to the plume location, with a simple smoke layer calculation for predicting the temperatures of structural members away from the burning region. Figures 1 and 2 schematically illustrate the proposed scheme.

Figure 1. New travelling fire model on an open plan office floor plate

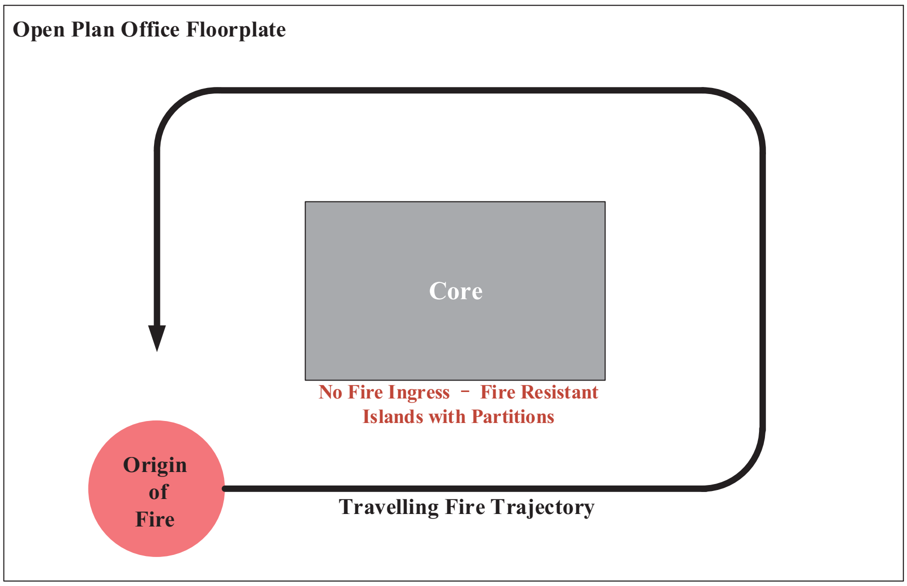
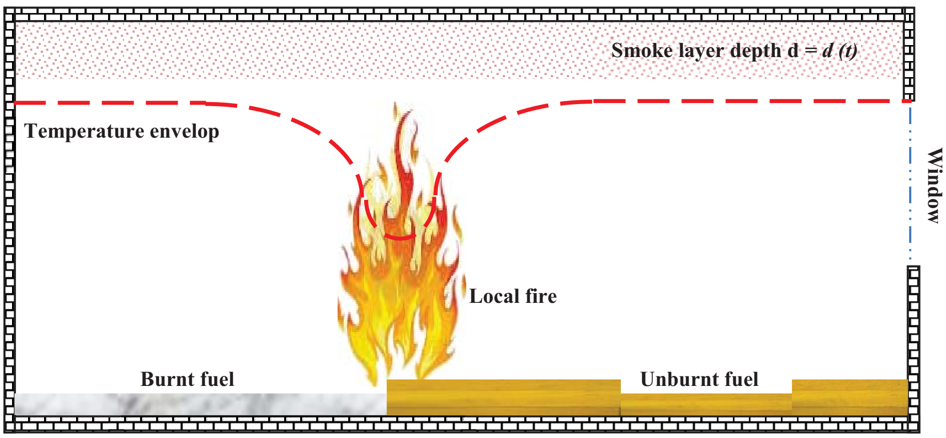


Figure 2. New travelling fire model in sectional elevation view



Near field: Hasemi localized fire model

For quantifying the local effect of the travelling fire on adjacent structural members, Hasemi's localized fire model[12] is utilized here. When the fire plume is impinging the ceiling, the net heat flux, $\dot{h}$ (W/m^2), is given in Eurocode 1[13] as,

$$\dot{h} = 100000 \qquad \text{if} \quad y \leq 0.30$$

$$\dot{h} = 136300 - 121000y \qquad \text{if} \quad 0.30 < y \leq 1.0 \qquad [1]$$

$$\dot{h} = 15000y^{-3.7} \qquad \text{if} \quad y \geq 1.0$$

The parameter y is obtained by calculating the following equation:

$$y = \frac{r+H+z'}{L_h+H+z'} \qquad [2]$$

Where r (m) is the horizontal distance between the vertical axis of the fire and the point along the ceiling where the heat flux is calculated, H (m) is the distance between the fire source and the ceiling, L_h (m) is the horizontal flame length given by the following relation:

$$L_h = (2.9H(Q_H^*)^{0.33}) - H \qquad [3]$$

With Q_H^* a non-dimensional heat release rate given by:

$$Q_H^* = Q/(1.11 \cdot 10^6 \cdot H^{2.5}) \qquad [4]$$

z' (m) is the vertical distance between the virtual fire origin and the fire source, which is given by:

$$z' = 2.4D\left({Q_D^*}^{2/5} - {Q_D^*}^{2/3}\right) \qquad \text{if} \quad Q_D^* < 1.0 \qquad [5]$$

$$z' = 2.4D\left(1.0 - {Q_D^*}^{2/5}\right) \qquad \text{if} \quad Q_D^* \geq 1.0$$

Where $Q_D^* = Q/(1.11 \cdot 10^6 \cdot D^{2.5})$, D (m) is the diameter of the fire, Q (W) is the heat release rate of the localised fire.

Hence, in order to employ Hasemi's localized fire model into the new travelling fire model, three key parameters should be decided beforehand: fire origin, fire diameter, D (m), and heat release rate, Q. Details of how these parameters are approximated according to the features of the travelling fire is illustrated in the following several sections.

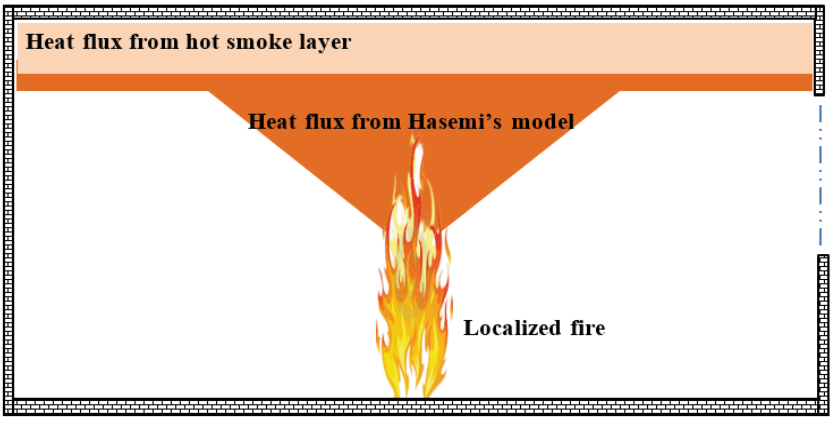
Far field: simple smoke layer calculation

The combination of energy conservation and smoke generation is brought into the travelling fire model in an elementary way, considering a varying distribution of fuel along the trajectory. The depth of the smoke layer is assumed to be time dependent and uniform over the whole ceiling. Smoke is considered to accumulate as more local lumped fuel is consumed, the rate of air entrainment is determined using a number of different models. This feature should reproduce pre-heating and post-heating effects for the structural analysis, which is the hallmark of a travelling fire.

Combination of the two models

Since Hasemi's equation is applicable to localized fires in an unconfined space and smoke accumulation is not considered in his model, this may lead to the far field predicted temperature based on Hasemi's localized fire calculation in a confined space being lower than the actual temperature. Therefore, it is proposed here to combine Hasemi's model with a hot smoke layer calculation. In other words, the radiant and convective heat fluxes to structural surfaces can be calculated based on the summation of heat flux from Hasemi's localized fire, and heat flux from the hot layer of the smoke (see Figure 3).

Figure 3. Heat fluxes superposition from two models



FIRE TRAJECTORY

As the final objective of this new travelling fire model is for application to structural analysis, the travelling fire trajectory is assumed to be under the mid-span of the main beams (see Figure 1), which would normally represent the worst case for the structural response.

REGULATORY MINIMUM FUEL DEPTH (RMFD)

The concept of a regulatory minimum fuel depth (RMFD) is introduced corresponding to a reference travelling fire spread rate, v, and fuel load density, $q_{f,k}$, in the model. This RMFD is a layer of fuel uniformly distributed over the entire floor plate, and contributes to the total heat flux calculation. Moreover, an agreed quantity of additional lumped fuel is placed next to the most critical and/or most vulnerable parts of the structure identified in consultation with the structural engineer according to performance-based design principles. Figures 4 & 5 illustrate how the travelling fire evolves based on the RMFD concept.

Figure 4. Elevation view - RMFD concept in 1D Travelling fire with one trajectory

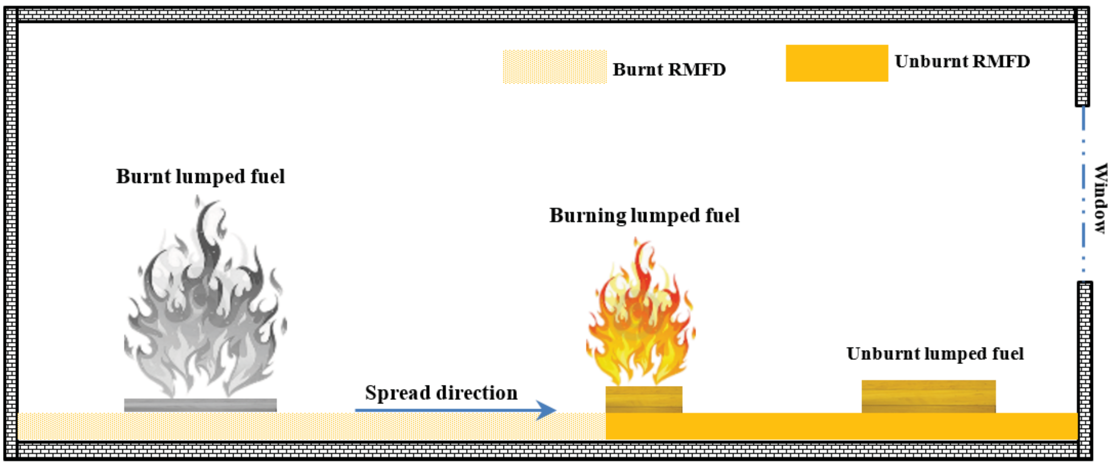
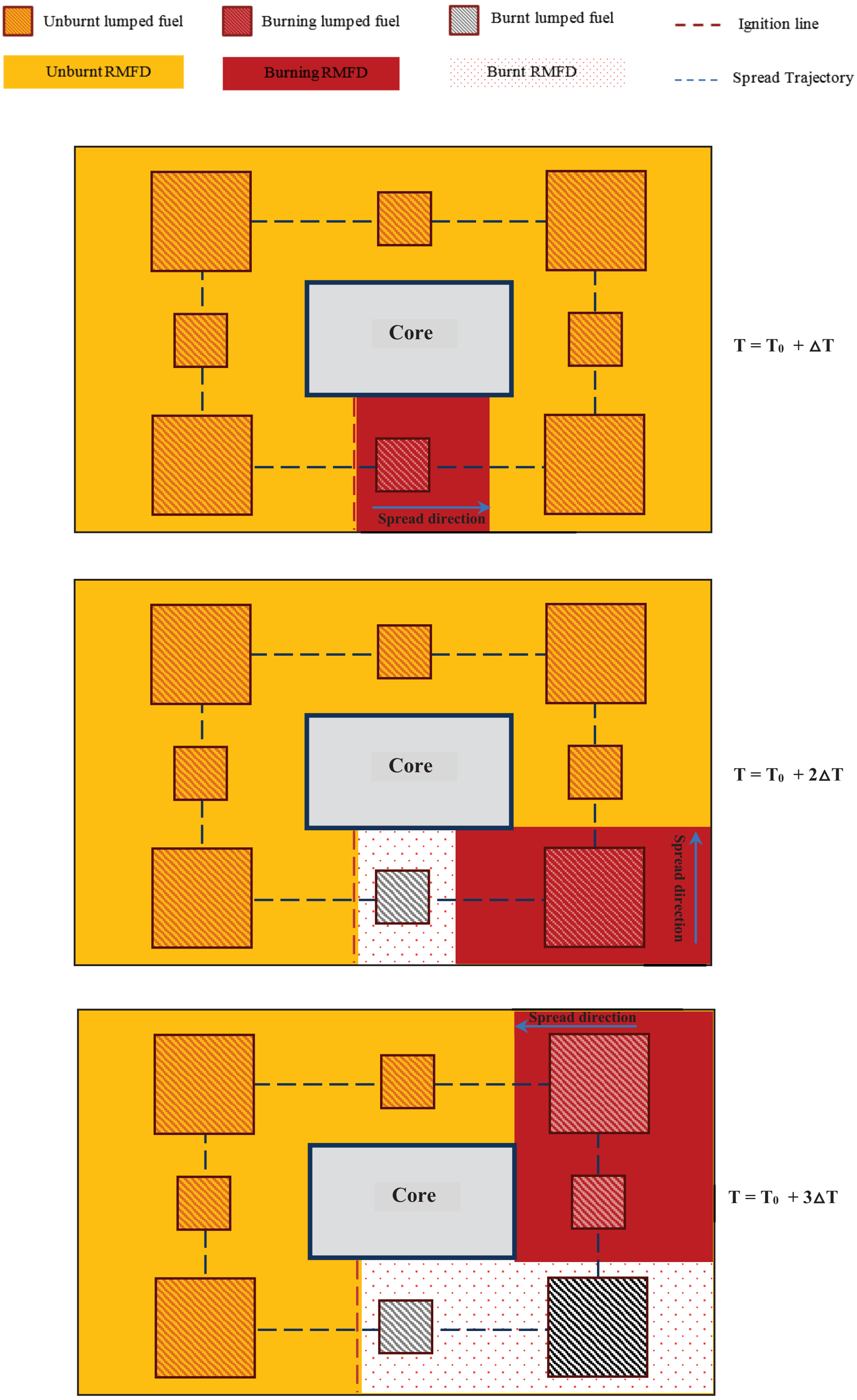


Figure 5. Plan view - RMFD concept in 1D Travelling fire with one trajectory



Fire spread rate v

The spread rate, v (mm/s), of the travelling fire front edge is assumed to be a constant, and bound with the concept of RMFD. Corresponding data can be extracted from some experiments and real fire observations, such as the summary done by Rackauskaite et al.[10].

Table 1. Fire spread rate v from experiments and real fire observations summarised by Rackauskaite et al.[10]

Details	Spread rates (mm/s)
Wood cribs in the open	0.1–2
Lateral or downward spread on thick solids	1
Tests on natural fires in large scale compartments	1.5–19.3
Reconstruction of WTC fires (2001)	2.5–16.7
St. Lawrence Burns tests (1958)	7.5–13
First Interstate Bank fire (1988)	14.5

Fuel load density $q_{f,k}$

In addition to the specification of the travelling fire spread rate, v (mm/s), the other parameter which is linked with the concept of RMFD is the characteristic fuel load density, $q_{f,k}$ (MJ/m^2). The reference values of $q_{f,k}$ for different occupancies can be found in Eurocode1[13], which is shown in the table below.

Table 2. Characteristic fire load densities $q_{f,k}$ depending on different occupancies from Eurocode 1[13]

Occupancy	Average	80% Fractile
Dwelling	780	948
Hospital (room)	230	280
Hotel (room)	310	377
Library	1 500	1 824
Office	420	511
Classroom of a school	285	347
Shopping centre	600	730
Theatre (cinema)	300	365
Transport (public space)	100	122
NOTE Gumbel distribution is assumed for the 80 % fractile.		

SPEED OF THE TRAVELLING FIRE

The speed of the travelling fire can be decomposed based on two variables: the constant fire spread rate, v, which determines the front edge location of the travelling fire, and the burn-out time, t_b, which determines the back edge location of the travelling fire, which will be introduced in the later sections. The resultant of these two variables decides the travelling fire centroid coordinates along the trajectory at each time step.

HEAT RELEASE RATE Q

The two most important parameters in this new travelling fire model are: travelling fire speed which determines how long the moving Hasemi localized fire will affect the structural element involved in the localised burning; and the heat release rate (HRR) of the travelling fire which determines the release of thermal energy per unit time. The heat release rate Q discussed in this section is to be used for implementing Hasemi's localized fire model according to equations [1] – [5] into the new travelling fire model.

Although in Eurocode 1[13] the expression for calculating HRR during the fire growth phase (t-squared fire evolution) is specified, the development phase of the travelling localized fire is not considered important from the structural design point of view. Due to the above reason, and for retaining the simplicity of the new travelling fire model, the heat release rate Q (W) is defined by the following expression according to Eurocode1[13]:

$$Q = 1000 \cdot RHR_f \cdot A_{fi} \tag{6}$$

Where A_{fi} (m^2) is the burning area of the fuel, RHR_f (KW/m^2) is the maximum heat release rate per unit area in fuel controlled conditions. The determination of RHR_f for different occupancies can be referred to Eurocode1[13], which is shown in the following table.

Table 3. Maximum RHR_f depending on different occupancies from Eurocode 1[13]

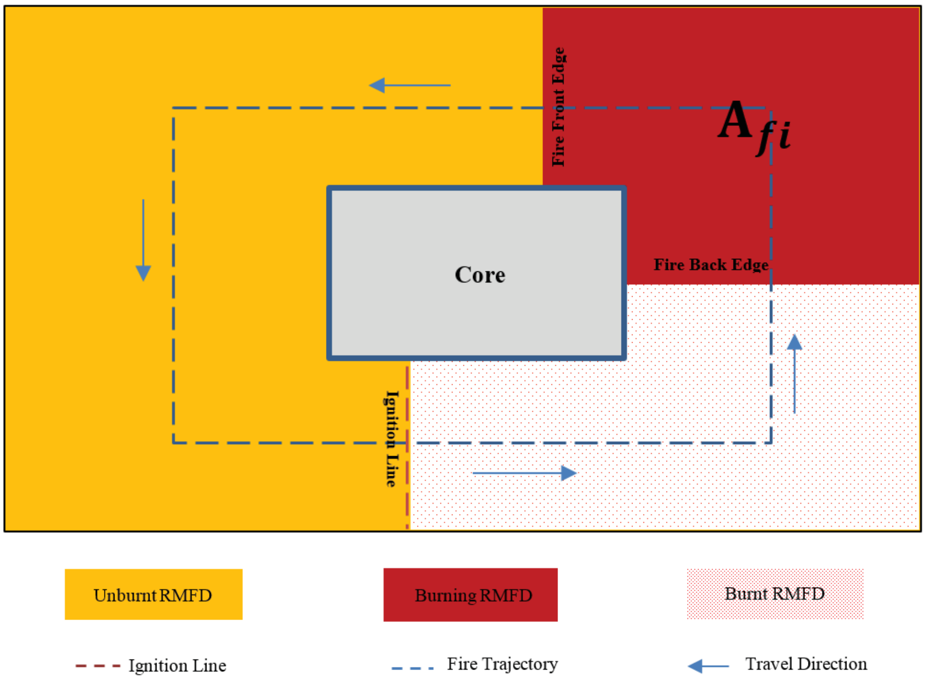
Max Rate of heat release RHR_f			
Occupancy	Fire growth rate	t_α [s]	RHR_f [kW/m^2]
Dwelling	Medium	300	250
Hospital (room)	Medium	300	250
Hotel (room)	Medium	300	250
Library	Fast	150	500
Office	Medium	300	250
Classroom of a school	Medium	300	250
Shopping centre	Fast	150	250
Theatre (cinema)	Fast	150	500
Transport (public space)	Slow	600	250

Since RHR_f is a value corresponding to the stationary state of the fire, it implies that the new travelling fire model is actually a 'partial post-flashover' fire which covers a certain burning area of the fuel, and travels on the floor plate as time evolves.

Burning area of fuel A_{fi}

As this new travelling fire model is basically a localized fire travelling along a predefined trajectory, the burning area of fuel A_{fi} (m^2) is determined by three variables: the travelling fire front edge location derived from the assumed constant fire spread rate, v, the travelling fire back edge location derived from the burn-out time, t_b , and the compartment width derived from the floor plan dimensions. Figure 6 illustrates how burning area of fuel, A_{fi}, is obtained schematically. For simplicity and clarity, the lumped fuel is not included in the drawing.

Figure 6. The determination of burning area of fuel A_{fi}



Burn-out time t_b

This new travelling fire model is assumed to be fuel-controlled, and all fuel would be consumed over the entire fire duration. Therefore, in order to determine the travelling fire back edge location, a burn-out time, t_b, is introduced into this new travelling fire model, which is a similar variable assumed in Rein's travelling fire model[10] for quantifying the time needed for burning out a certain area of fuel completely. Burn-out time, t_b (s), is obtained by the following equation:

$$t_b = 1000 \cdot q_{f,k}/RHR_f \qquad [7]$$

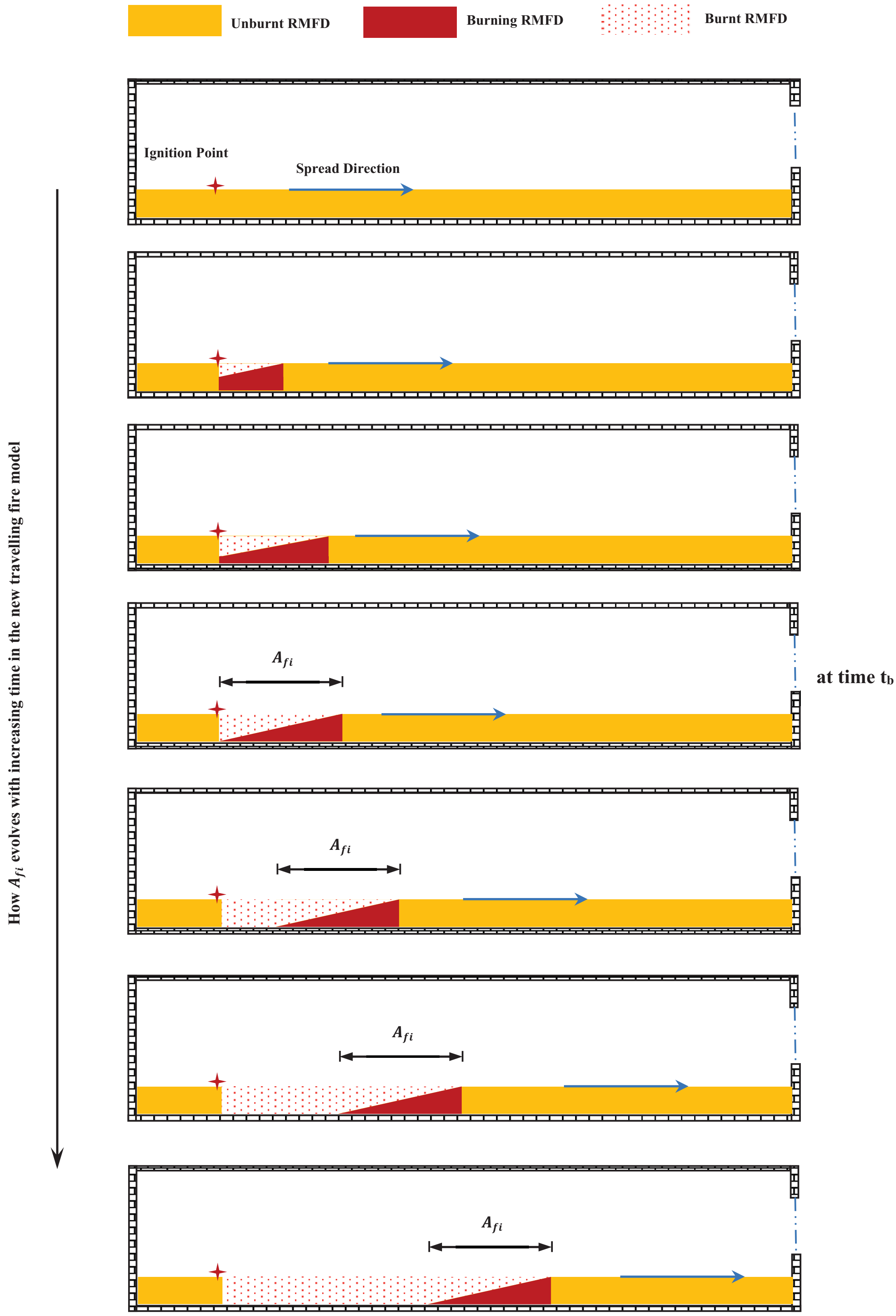
Where $q_{f,k}$ (MJ/m^2) is the characteristic fuel load density, RHR_f (KW/m^2) is the maximum heat release rate per unit area in fuel controlled conditions. These two parameters can be determined according to Table 2 & Table 3 respectively. Figure 7 schematically illustrates how the burning area of fuel A_{fi} is determined with the burn-out time t_b concept. For simplicity and clarity, lumped fuel is not included in the drawing.

APPROXIMATION OF FIRE ORIGIN AND FIRE DIAMETER *D*

Once the burning area of fuel A_{fi} is determined, fire origin of the travelling Hasemi's localized fire model can be obtained, which is defined as the centre of the distance between the travelling fire front edge and back edge along the trajectory. Furthermore, the fire diameter D (m) of the travelling Hasemi's localized fire, can be approximated as the diameter of a circular source of the same burning area of fuel A_{fi} (m^2), which is given by:

$$D = \sqrt{4 \cdot A_{fi}/\pi} \qquad [8]$$

Figure 7. Elevation view – determination of burning area of fuel A_{fi} with t_b concept



OTHER KEY ASSUMPTIONS

The proposed design fire is fuel controlled based on the assumption that sufficient air is available at the beginning and subsequently the glazing adjacent to the fire plume breaks. All fuel is assumed to be consumed over the design fire duration with: non-uniform burning rates of the travelling fire along the trajectory; changing fuel load density; and variable heat release rates. A flashover scenario arises naturally in this model and the fire transitions from a localized travelling fire to a whole compartment fire when the temperature of the hot smoke layer reaches 500°C[14], as discussed below.

Ignition point

The ignition point of the travelling fire could be anywhere in the compartment. However, a fully developed localized fire will be the initial state of this travelling fire model, at which point it becomes mobile. From the structural design point of view, the development phase of the localized fire is not considered important, just as the pre-flashover stage is often ignored in compartment fires.

Flashover

When flashover occurs in the compartment, there are three commonly-used indicators[18]: 1) the temperature of the smoke in the whole compartment reaches to 500^{o}C; 2) heat fluxes produced from the fire are as high as 20 KW/m^2 at the floor level; 3) For ventilation-controlled fire, flames 'flow' out of the window.

Although the above three are simply indicators of the flashover state, clause 2) is still used for the implementation of the new travelling fire model in SIFBuilder framework[15], which will be introduced in the following section. In other words, once the temperature of the hot smoke layer reaches 500^{o}C, the fire would transit from a travelling fire to a whole compartment fire.

IMPLEMENTATION IN SIFBUILDER

The SIFBuilder[15] programming project was started in 2014, aiming to facilitate automated thermo-mechanical analyses for large structures under a wide range of idealised fires, some of which mimic realistic fire exposures (such as localized and so-called travelling fires). The special features of SIFBuilder include: large model generation with minimal input; rapid heat transfer analysis for a range of idealized-uniform and idealized non-uniform fires; automatic coupling of the heat transfer output with the structural model to perform thermo-mechanical analyses.

This new travelling fire model is programmed into SIFBuilder based on previous work[15,16], which is mainly about the development of the OpenSees software framework for integrating the heat transfer and thermo-mechanical analysis for modelling localized fire in structures. The implementation of this new travelling fire model in SIFBuilder follows the same workflow as the localized fire model. After inputting basic structural information for generating the structural model, the user defines the structural loading and thereafter the fire loading information. The travelling fire module interacts with the heat transfer module through their respective interfaces at each time step in order to determine the transient fire imposed boundary conditions adjacent to the structural surfaces.

Unlike the localized fire model in SIFBuilder, both spatially and temporally non-uniform heat fluxes for different structural elements produced from the summation of the heat flux from the hot smoke layer and Hasemi's model, are updated at each time step according to the travelling fire location in the compartment (see Figures 8 and 9, only one structural element shown for clarity).

Figure 8. Heat flux at time t_0

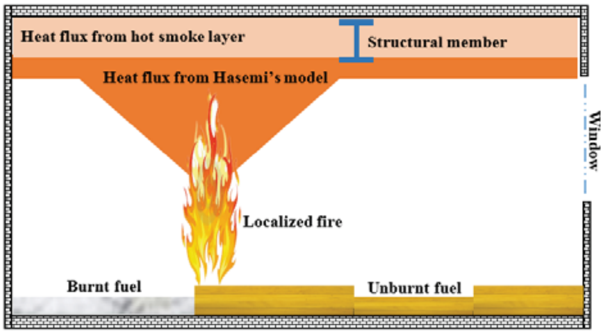
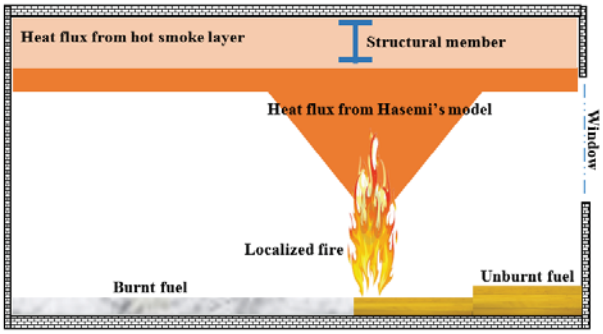


Figure 9. Heat flux at time $t_0 + \Delta t$



Subsequently, the heat transfer analysis module launches and the nodal temperature histories are automatically mapped to the fibres of the structural elements for each structural member. Following the heat transfer analysis the thermo-mechanical analysis module is invoked to determine the structural response history for the whole frame including all heating phases for each structural member. This may include the effects of preheating, direct heating, post-heating and cooling.

Ultimately, the new tool will provide a flexible approach for examining the impact of fire on structural behaviour under realistic design fire scenarios at a greatly reduced cost, in terms of analysis time and user effort, than currently possible. Detailed implementation of this new travelling fire model in SIFBuilder can be found in a previous publication[17].

LIMITATIONS OF THE NEW TRAVELLING FIRE MODEL

This new travelling fire model is developed for providing a more realistic tool for structural design for fire resistance, hence there are several inevitable limitations in the model. Firstly, the model is fuel-controlled and ventilation is not considered. Secondly, it is essentially a 1D trajectory-based travelling fire model, which is currently only applicable to floor plans with a core. Finally, the application of Hasemi's localized fire model is valid when the fire diameter D is less than 10m, and the rate of heat release Q is limited to the maximum value of 50 MW, when very large compartments are considered according to Eurocode 1[13].

CONCLUSIONS

This paper presents a new travelling fire model in support of performance-based methodologies, for structural engineers to quantify the realistic impact of a fire in modern open plan buildings, and it is by definition designed to determine the whole structural response. Although further study of applications is required, the authors believe that it represents a conceptual idea for a more usable travelling fire model in the context of structural fire resistance. Work is continuing on the programming of this scheme in OpenSees/SIFBuilder, and the development of a set of case studies for the verification and validation of the proposed framework (not discussed further due to restriction of space).

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